TRANSACTIONS
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ILLUMINATING ENGINEERING SOCIETY

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VOLUME XX
No. 2 — 1955

32 VICTORIA ST
LONDON, SW1

Annual Subscription to Non-Members - £2.2.0
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A Method of Evaluating Seeing Distances on a Straight Road for Vehicle Meeting Beams

By V. J. JEHU, M.Sc., A.Inst.P.

Summary

The paper describes a method of calculating the distances at which objects may be seen in the light of a driver's own headlamps when one vehicle meets another on a straight road. It is based on experimentally determined seeing distances for beams of uniform intensity, obtained when the observer's vehicle was moving at 30 miles per hour and the glare lamp was stationary. The data, which were obtained for a given road width and position of the test object, are extended to other widths and object positions by means of the Stiles-Holladay law that the effect of a glaring light varies inversely as the square of the angular separation between the glare source and the line of sight.

The method has been used to evaluate seeing distances for four object positions across the road for a meeting beam typical of current British and American practice in which the beams are deflected to the nearside. The results show that with this system of lighting the minimum seeing distance for an object in the nearside lane occurs when the object is somewhat nearer the driver than the opposing lamps, and that the value of the minimum direct seeing distance varies considerably with the position of the object across the road.

Comparisons between calculation and measured seeing distances in trials in which both vehicles were moving are in good agreement for objects along the nearside of the road. At other object positions comparison is not possible at present because the experimental evidence available is insufficient.

Introduction

The comparison of the performance of two different meeting beams by purely experimental methods is a tedious and difficult process. It was found, for example, that when trials were carried out in Holland in 1949([1]) to compare the seeing distances obtained with various types of meeting beam on straight roads, differences due to the beam distributions were masked by the variability of the results. In the present paper a method is described by which seeing-distance curves can be calculated for a given beam distribution from a relationship found experimentally between the more important parameters involved in a particular meeting situation. This method of approach simplifies the experimental technique, and the results can be applied to any desired meeting beam. Differences in the seeing-distance curves obtained by the method are therefore due solely to differences in the beam distributions. Other advantages of the method are that it can be applied to many more meeting situations than it would be possible to examine by means of full-scale trials, and that it avoids some of the difficulties which arise when it is desired to compare results obtained by one set of experimenters with those obtained elsewhere by others in slightly different experimental conditions, as when tests are carried out in different countries.

Outline of Method

Briefly, the method used to evaluate seeing distances for opposing meeting beams is as follows. By tests using beams of uniform intensity the relationship has been found between the intensity directed at a specified object, the glaring intensity of the opposing stationary lamp, and the distance away at which the object was identified by an observer in a moving vehicle. The data obtained make it possible to evaluate

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The manuscript of this paper was first received on May 14, 1954, and in final form on September 27, 1954.

the beam intensities needed at various distances to see the object in its standardised position relative to the glare lamp, when the glaring intensities of a given meeting beam are evaluated from its beam distribution diagram. The distance at which the required beam intensity and that actually directed at the object are the same is the distance at which the object will first be recognised. The law that the effect of a glaring light varies inversely as the square of the angular separation between the glare source and the line of sight, enables the basic data to be extended to deal with other object positions, so that seeing distances can be evaluated for meeting beams from more than one lamp and for a variety of object positions.

The Meeting Situation

When two vehicles meet at night an object on the road between the vehicles may be seen either as a dark silhouette against the patch of road surface brightened by the lamps of the oncoming vehicle, or it may be seen directly in the light of the driver's own headlamps. "Silhouette seeing" usually occurs during the earlier stages of a meeting situation and is not considered in this paper.

Whether or not a driver can see an object on the road in his own meeting beam will depend on a number of factors. The most important of these are the luminance factor of the object, its position across the road with respect to the opposing meeting beam, the distance between the vehicles, the beam intensity aimed at the object by the driver's meeting beam, and the glaring intensity to which he is subjected from the opposing beam. Other less important factors influencing the seeing distance at a given instant are the contrast between the object and its background which will be different for different road surfaces, and the whole beam distribution of the two opposing meeting beams, of which the particular beam intensity on the object and the glaring intensity form only a part. Experiments suggest, however, that under clear weather conditions these factors do not greatly influence observations made in a moving car, and they have been ignored in this paper.

Because the object of the calculations is to compare the performance of different types of meeting beam, the luminance factor of the object can be standardised, so that for a specific position of the object with respect to the opposing beam the beam intensity aimed at the object and the intensity of the glare will largely determine the distance ahead at which the object will be seen. The relationship between these three factors has been determined experimentally for a standard test situation.

Basic Data

Measurements were made at 30 miles per hour on a straight road, of the distances at which the shape of an object having a luminance factor of 7 per cent. was recognised. To ensure a constant beam intensity directed at the object during the test runs, a headlight was used giving a uniform intensity over a spread of 8 deg. both horizontally and vertically. The glaring intensity was kept constant by using a beam with a horizontal spread of 20 deg. mounted at the same height above ground as the observer's eyes. Only one lamp was used to give each beam. Between test runs the intensities of the opposing beams could be varied by alteration of the supply voltages.

The test objects, a circle of diameter 1 ft. 6 in. and a rectangle 1 ft. 9 in. by 1 ft., were placed on the road at a sideways separation of 10 ft. from the glare source and 10 ft. behind it. The objects were, therefore, always recognised by direct vision and never as a silhouette against an area of road surface lighted by the glaring lamp. The rectangle was placed with its long or short sides vertical according to random choice.

In this way the relationship shown in Fig. 1 was found between the intensity of the beam directed at the object, the glaring intensity, and the distance at which

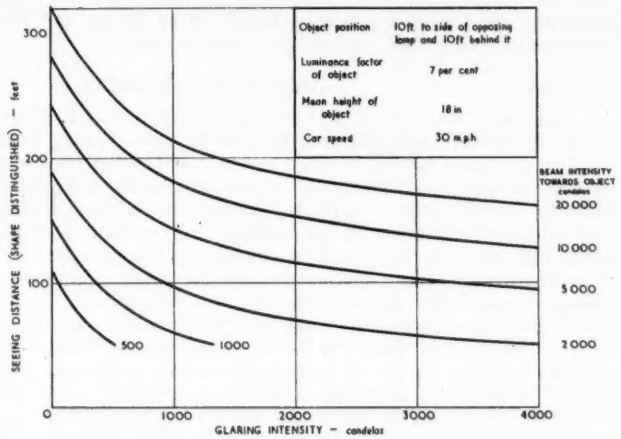


Fig. 1. The relation between seeing distance, beam intensity directed at an object, and glaring intensity.

the shape of the object was recognised. The curves of Fig. 1 are based on the smoothed-out curves of the results of one observer. Since the object is mainly to obtain comparative figures for seeing distance, little significance attaches to the fact that these results are not necessarily those of the average observer. It is known that the observer has normal vision with spectacles, and obtains results in such tests which are compatible with those of other observers.

The constant factors in the situation to which the results of Fig. 1 apply are :—

(1) the position of the object in relation to the glare lamps,
(2) the distance between the path of the driver of the vehicle and the glare lamps,
(3) the area and approximate shape of the object,
(4) the luminance factor of the object,
(5) the luminance factor of the background, and
(6) the speed of the vehicle.

Assumptions Underlying the Method of Calculation

In applying the results obtained with opposing uniform beams to actual meeting beams the following assumptions are made :—

(i) it is assumed that differences in the luminance of the road surface, due to differences between the distribution of light from the test lamps and from those lamps for which the calculations are made, do not affect seeing distance;
(ii) it is assumed that when beams of non-uniform intensity are used, the seeing distance at any moment depends on the intensities responsible for glare and for illumination at that moment;
(iii) it is assumed that the whole of an object 18 in. high must be illuminated by a beam of at least the intensity given by Fig. 1 before it is seen.

The beam distributions of the lamps used to obtain the experimental results were such that the intensity of the beam directed at the object and also the glaring intensity directed towards the observer were independent of the relative positions of object, observer's vehicle and glare source over the measured range of seeing distances. With practical meeting beams, however, these intensities vary with the relative positions. For this reason it is necessary, when applying the relationship given in Fig. 1 to actual meeting beams, to consider not only the distance of the glare source and the observer from the object but also their heights above the road. In this paper the

observer's eye height has been assumed to be 50 in. and the lamp height 30 in., these values being fairly typical for modern cars.

Method of Calculation

The basic data, which give the seeing distance of a given object as a function of the illuminating intensity and the glaring intensity, may be used to find the seeing distance on the same test layout for any combination of single-lamp meeting beams by considering at each separation of the vehicles the intensity illuminating the object and the intensity from the glaring source. As already stated, these intensities will vary with the separation of the vehicles for practical meeting beams. The way in which they vary can be found by considering the geometry of the meeting situation in relation to the beam distributions of the opposing lamps. The relation between glaring intensity and distance between the vehicles can be converted by means of Fig. 1 into beam intensities, which must be aimed at the object in order that it may be seen through the glare. If for a given distance between the vehicles the actual intensity aimed at the object exceeds that shown to be necessary by Fig. 1, the object will be visible. The distance at which the required beam intensity and the actual intensity aimed at the object are the same is the distance at which the object will first be recognised.

So far the situation being considered is the same as that of the basic test, i.e., the opposing beams come from single lamps, the object is restricted to a definite position relative to the glaring vehicle, and the road has a definite width. The work may be freed from these restrictions, however, by virtue of the Stiles-Holladay relation which states that the glaring effect of a light is inversely proportional to the square of the angle between the direction of the light and the line of vision(2). This was established for the effect of glare on just perceptible differences of luminance under laboratory conditions, but there is some reason to suppose that it holds for conditions such as those under discussion. Assuming this law the basic data found for single lamps, one width of road, and one object position, may be used to deal with meeting beams from more than one lamp, an arbitrary road width and any desired object position. The way in which the law has been used is explained in detail in the appendix.

Application of Method

The situation selected for evaluation in this paper is that in which two vehicles, each travelling in the centre of its respective lane, meet on a road 20 ft. wide, so that the distance across the road between the axes of opposing sets of lamps is 10 ft.

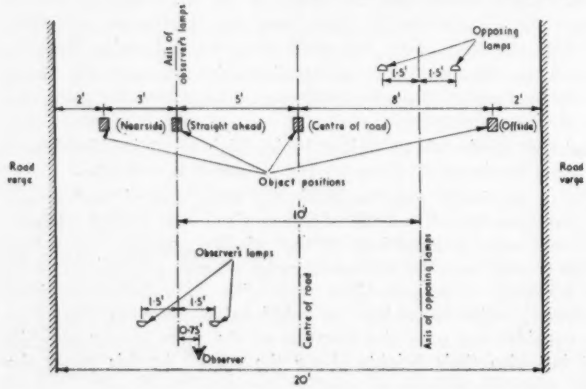
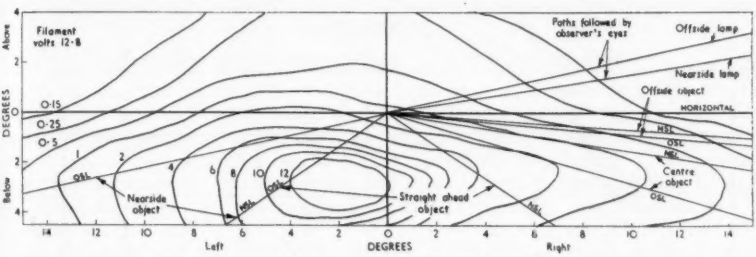


Fig. 2. The assumed arrangement of observer, lamps and object positions on a 20 ft. road.



Figures to curves denote beam intensity in candelas × 10^3
NSL denotes nearside lamp
OSL denotes offside lamp

Fig. 3. Beam distribution from one lamp of a modern British meeting system.

The lamps on the vehicles are assumed to be 3 ft. apart, and four object positions across the road have been considered. The selected arrangement is shown in Fig. 2. The system chosen for evaluation is an example of one of the two common head-lighting systems in use to-day. This is the modern British double dipping system, which is typical of current British and American practice, in which the lamps are aimed by means of the driving beams. The meeting beams are both dipped and deflected to the nearside. The particular case considered is that in which the lamps on both vehicles are correctly aimed.

The paths followed by the observer's eyes when the beam distribution is considered respectively as from the nearside glare lamp, and as from the offside glare lamp, are shown in Fig. 3, which also shows the paths followed by the top of the object in its four positions across the road when the beam distribution is considered to be from the observer's nearside lamp, or from the offside lamp.

Seeing-distance curves for the four object positions are shown in Fig. 4, from which it will be seen that with this type of meeting beam the value of the minimum seeing distance varies considerably with the position of the object across the road. The low values of seeing distance for objects in the centre and on the offside of the road correspond to circumstances when seeing by silhouette is considerably enhanced owing to the proximity of the glare source, and also therefore of the bright patch on the road, to the observer's line of sight. Fig. 4 also shows the line dividing the region in

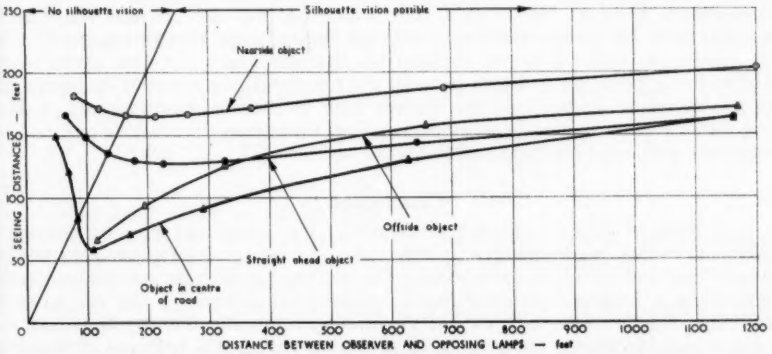


Fig. 4. Direct seeing distance curves for objects on a 20 ft. road with double-lamp British meeting beam.

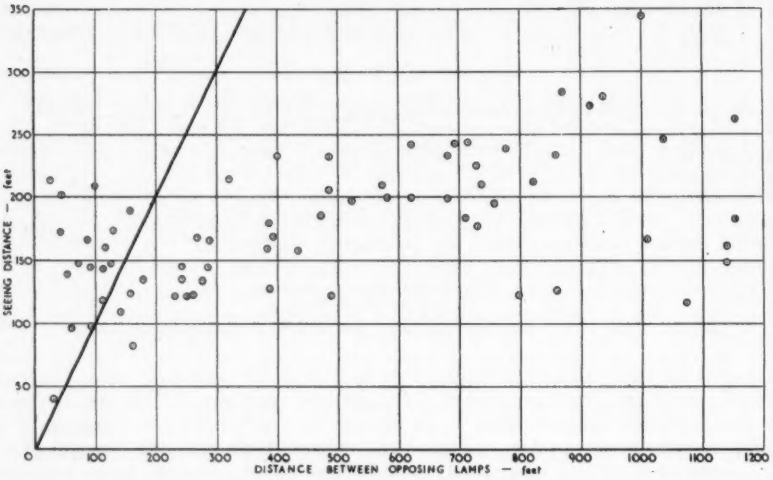


Fig. 5. Measured seeing distances for a small object on the nearside of the road with opposed American sealed beam lamps.

which seeing by silhouette is possible (because the objects are between the cars) from that in which it is impossible (because the objects are behind the glare car). The minimum seeing distance with the British lamps for objects on the nearside, straight ahead, and in the centre of the road, occurs before this dividing line is reached, i.e., seeing is most difficult when the object is somewhat nearer to the observer than the opposing lamps.

For comparison, Fig. 5 contains the seeing distances obtained in Holland([1]) for an object 16 in. high with a luminance factor between 9 per cent. and 10 per cent., placed about 18 in. inside the nearside lane, in a test arrangement in which both vehicles were travelling at 40 miles per hour on a road about 20 ft. wide. American sealed beam lamps were used in these tests. It is immediately obvious that the scatter in the results from full-scale tests of this kind is considerable. Most of the measurements, however, lie within a zone which has the same general shape as the calculated curve for the nearside object with the British lamps, though apparently somewhat steeper; a further point of similarity is that the absolute values of the seeing distances for a mean curve drawn through the measured points would be comparable with the calculated values. At the present time insufficient measurements of direct seeing distance have been made at object positions other than the nearside one, to allow comparison with the remaining calculated curves.

Conclusion

It is believed that the method described in this paper can provide answers to problems in vehicle headlighting, solutions to which have previously been attempted by means of long and costly full-scale trials. The method has been used to evaluate seeing distances for a particular meeting beam. Apart from examining the effects of the distribution of light in those regions of the meeting beam affecting the illumination of the object and the glaring intensity, other problems, such as the influence of headlamp height on beam performance, and the effect of tinted windscreens on seeing at night, could be investigated in the same way.

Appendix

Extension of the Basic Data to the General Case

Fig. 1 enables the seeing distance of the test object in the standard test situation to be found for various types of beam distribution from opposing single lamps. Consideration of the geometry of the meeting situation and the well-known equivalent luminance expression for a glare source enable the relationship of Fig. 1 to be applied to other arrangements of observer, object and glare source, so that the way in which seeing distance varies as two opposing vehicles approach one another can be investigated.

Thus Luckiesh and Holladay[3] found that the effect on the perception of the threshold differences of luminance of a light source in the field of view is the same as a veiling luminance superposed on the object and background alike. The expression for the equivalent veiling luminance may be written

$$\frac{k\,G}{D^2\,\theta^n}$$

in which

G = glaring intensity,

θ = angle subtended at the observer's eyes by the line joining object and glare source,

D = distance between observer and glare source,

and k and n are constants.

The equivalent veiling luminance from a number of lamps is obtained by summing their individual values. It will be seen from this expression that the glare effect of a given intensity G is a function of its location with respect to the observer, both as regards its distance and its direction.

Static outdoor experiments show that the value of the integer n is not very different from 2[2]. Assuming this value of n applies also to dynamic tests, and considering the general situation of a glare source, object and observer shown in Fig. 6, we have approximately for the angle θ between the observer's line of sight and the line joining observer and glare source,

$$\theta = \frac{\sqrt{(x-x')^2+(y-y')^2}}{d+r}$$

in which

$$x' = p\,\frac{d+r}{d}$$

$$y' = h + \frac{r}{d}\,(h-z)$$

Thus the denominator of the glare term $D^2\,\theta^2$, which is approximately equal to $(d+r)^2\,\theta^2$, becomes

$$(x-p)^2 + (y-h)^2 + \frac{2r}{d}\left[p^2 - xp - (y-h)\,(h-z)\right] + \frac{r^2}{d^2}\left[p^2+(h-z)^2\right]$$

an expression in which specific values can be assigned to the various parameters for the meeting situation at any particular instant.

Substitution of the values appropriate to the test situation enables the denominator to be evaluated in terms of the distance d; thus for the test situation

$p = -0.75$, $r = -10$, $x = 9.25$,

and for the purposes of comparing practical meeting beams it has been assumed that

$y = 2.5$, $z = 4.17$.

The values of the denominator for the test situation are given in Table 1 for different values of d.

Substitution of other values of p, r and x corresponding to movement of the

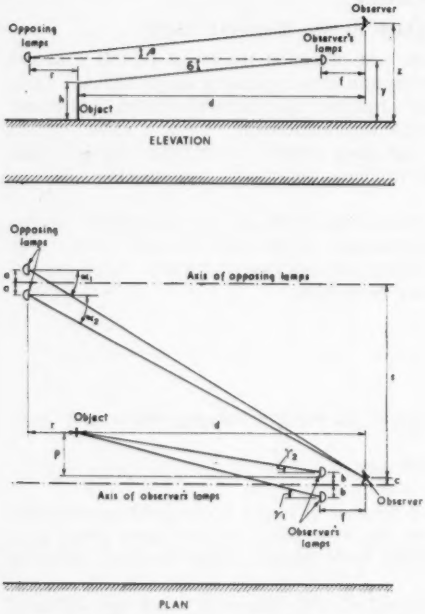


Fig. 7. The relative positions of observer, object and opposing lamps.

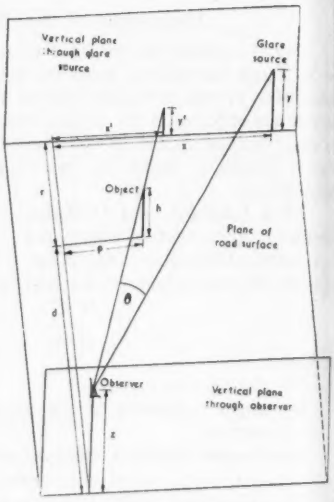


Fig. 6. Oblique projection showing the relative positions of observer, object, glare source and angle θ.

Table 1

Values of the Denominator of the Glare Term for the Test Situation

$$\text{Denominator} = 101 - \frac{20}{d} \times 10.17 + \frac{100}{d^2} \times 7.6914$$

d (ft)	Denominator (D_1)
50	97.24
100	99.04
150	99.68
200	100.00
250	100.20
300	100.33

object across the road, and of the glare source along and across the road, enables the denominator to be calculated for other situations.

For a given value of d, the resultant glare effect for a situation in which p, r and x differ from those of the test situation, will be proportional to the ratio of the value of the denominator calculated for the test situation, to that appropriate to the situation under investigation. Thus for any situation the glaring intensity is converted, both for distance and direction, into an equivalent intensity at the standard test situation, which would produce the same glare effect at the observer's eyes. The ratio of the value of the denominator at the test situation to that at any given situation has been called the "glare multiplying factor." It is the factor by which the glaring intensities obtained from the beam distribution diagram at given values of d, r and x must be multiplied to convert them to equivalent glaring intensities at the same value of d, but at the values of r and x corresponding to the test situation, taking into account differences in the position of the object across the road in the two cases.

In this way the relationship given in Fig. 1 can be applied to calculate seeing-distance curves as two vehicles approach one another (different values of r) for different object positions across the road (different values of p), for meeting beams from more than one lamp (different values of x).

The Method of Calculation for Double-Lamp Meeting Systems

Fig. 7 shows the general arrangement for two opposing vehicles on each of which the meeting beam comes from two lamps.

The glaring intensity directed towards the eyes of the observer at a given separation d of the observer and the object is found by first determining the angles α_1 and α_2, which represent the sideways displacements of the observer from the two opposing lamps, and also the angle β, which represents the angle between a horizontal plane and a plane joining the observer's eyes to the centres of the opposing lamps. These angles, and the similar angles γ and δ for the object, also form the co-ordinate system in which the beam distribution of Fig. 3 is plotted. From Fig. 7

$$\tan \alpha_1 = \frac{s + a}{d + r}$$

$$\tan \alpha_2 = \frac{s - a}{d + r}$$

$$\tan \beta = \frac{z - y}{d + r}$$

in which s has a positive sign when measured to the right of the observer, and r is positive when the object is between the opposing lamps.

For a given meeting situation a, r, s, y and z will be constants and d a variable. The values of α_1 and β obtained for the nearside lamp, and similarly the values of α_2 and β for the offside lamp, are then plotted on the respective beam distributions of the opposing lamps to find the glaring intensities of each lamp at different separations of the object and observer. These glaring intensities are multiplied by the appropriate glare multiplying factors to convert them to equivalent glaring intensities for the standard situation, and the sums of the resultants for the two lamps are plotted on Fig. 1 with distance d as ordinate, and the points joined to form a continuous curve. From the readings obtained at the intersections of this curve with the curves of constant beam intensity on the object, another curve can be drawn relating the

Table 2

Values of the Glare Multiplying Factor D_1/D_2

(D_2 is the value of the denominator of the glare term at situations other than the test arrangement)

Object position p (ft.)	Glare lamp position x (ft.)	Observer position d (ft.)	Glare multiplying factor at the following values of r							
			+1000 (ft.)	+500 (ft.)	+200 (ft.)	+100 (ft.)	+50 (ft.)	0 (ft.)	− 50 (ft.)	− 100 (ft.)
− 3.75	10.75	100	0.028	0.075	0.189	0.286	0.362	0.469	0.621	0.837
		150	0.052	0.120	0.248	0.336	0.396	0.472	0.568	0.689
		200	0.076	0.159	0.289	0.365	0.415	0.473	0.543	0.627
		250	0.100	0.191	0.317	0.385	0.426	0.474	0.529	0.593
		300	0.121	0.218	0.338	0.399	0.435	0.475	0.521	0.571
− 3.75	7.75	100	0.031	0.088	0.247	0.403	0.537	0.743	1.068	1.576
		150	0.059	0.148	0.340	0.489	0.600	0.748	0.949	1.221
		200	0.089	0.202	0.406	0.542	0.635	0.750	0.895	1.078
		250	0.119	0.250	0.455	0.578	0.657	0.752	0.865	1.002
		300	0.149	0.291	0.492	0.604	0.675	0.753	0.859	0.955
− 0.75	10.75	100	0.088	0.226	0.473	0.606	0.676	0.743	0.800	0.837
		150	0.159	0.339	0.563	0.657	0.704	0.748	0.788	0.820
		200	0.228	0.420	0.611	0.683	0.717	0.750	0.781	0.807
		250	0.289	0.479	0.641	0.698	0.726	0.752	0.776	0.799
		300	0.341	0.522	0.661	0.708	0.731	0.753	0.774	0.793
− 0.75	7.75	100	0.097	0.278	0.706	1.000	1.176	1.352	1.500	1.576
		150	0.186	0.455	0.898	1.123	1.244	1.361	1.464	1.543
		200	0.281	0.600	1.010	1.187	1.278	1.365	1.445	1.512
		250	0.373	0.715	1.082	1.226	1.298	1.368	1.433	1.490
		300	0.458	0.804	1.131	1.252	1.312	1.370	1.424	1.474
+ 4.25	10.75	50	0.010	0.047	0.376	2.200	5.248	2.248	0.821	0.399
		100	0.048	0.234	2.103	5.345	4.028	2.290	1.329	0.837
		150	0.120	0.636	4.378	4.706	3.389	2.305	1.590	1.136
		200	0.236	1.317	5.195	4.065	3.092	2.312	1.745	1.342
		250	0.406	2.267	5.032	3.668	2.923	2.317	1.847	1.490
		300	0.640	3.339	4.667	3.413	2.816	2.320	1.919	1.601
+ 4.25	7.75	50	0.010	0.042	0.294	1.492	6.926	7.339	1.547	0.597
		100	0.043	0.190	1.455	7.060	13.47	7.475	3.119	1.576
		150	0.103	0.471	3.723	12.19	12.60	7.523	4.121	2.448
		200	0.192	0.912	6.780	13.61	11.47	7.547	4.780	3.150
		250	0.314	1.537	9.718	13.32	10.68	7.562	5.235	3.705
		300	0.474	2.358	11.80	12.70	10.15	7.572	5.568	4.149
+12.25	10.75	50	0.001	0.006	0.036	0.136	0.480	29.92	—	—
		100	0.006	0.024	0.138	0.489	1.557	30.47	4.604	0.837
		150	0.014	0.053	0.294	0.985	2.868	30.67	14.90	2.213
		200	0.024	0.092	0.494	1.573	4.239	30.77	39.22	4.653
		250	0.037	0.140	0.729	2.215	5.579	30.83	89.46	8.668
		300	0.053	0.197	0.992	2.887	6.853	30.87	167.2	15.00
+12.25	7.75	50	0.001	0.006	0.032	0.110	0.331	4.576	—	—
		100	0.006	0.022	0.112	0.337	0.837	4.661	36.02	1.576
		150	0.013	0.046	0.219	0.593	1.290	4.691	524.6	7.094
		200	0.022	0.077	0.340	0.845	1.667	4.706	46.08	36.63
		250	0.033	0.114	0.467	1.082	1.978	4.715	22.67	626.2
		300	0.047	0.154	0.597	1.299	2.235	4.721	15.80	528.1

distance of the object to the intensity which must be aimed at the object in order that it may be seen at that distance through the glare from the opposing lamps.

To evaluate the beam intensities aimed at the top of the object at a specified distance d the values of the angles γ_1 and γ_2, the sideways deflections of a vertical line through the centre of the object from the observer's lamps, are calculated, together with the angle of dip δ between the lamps and the top of the object. From Fig. 7

$$\tan \gamma_1 = \frac{p + b + c}{d - f}$$

$$\tan \gamma_2 = \frac{p - (b - c)}{d - f}$$

$$\tan \delta = \frac{h - y}{d - f}$$

in which p has a positive sign when measured to the right of the observer.

For a given meeting situation b, c, f, h, p, and y will be constants, so that by substituting values of d the corresponding values of γ_1, γ_2 and δ are found and plotted on the beam distribution diagrams as in Fig. 3, to find the contribution of each lamp to the intensity directed at the object at different separations of object and observer. A curve relating beam intensity on the object with its distance away can be drawn on the same axes as the curve already obtained relating distance of the object to the intensity necessary to see it through the glare from the opposing lamps. The intersection of these two curves determines the distance at which the 18-in. object will be seen for the particular arrangement of object, observer and glare source.

Specific values of r are selected for each of four values of p, and the procedure for finding the seeing distance of an 18-in. object is applied at each value of r. The seeing distance d is then plotted against $d + r$, the distance of the approaching vehicle's lamps from the observer, as in Fig. 4.

The Assumed Meeting Situation

The situation evaluated in this paper, the results of which are given in Fig. 4, is that in which two vehicles meet on a 20-ft.-wide road. The values assumed for the various parameters in the expression for the denominator of the glare term are as follows:—

$x = s + a = 10.75$	for the nearside glare lamp,
$x = s - a = 7.75$	for the offside glare lamp,
$p = -3.75$	for the nearside object,
$p = -0.75$	for the object on the axis of the observer's vehicle,
$p = +4.25$	for the object in the centre of the road,
$p = +12.25$	for the object on the offside of the road,

in which p is considered to be positive when measured to the right of the observer,

$h = 1.5$	for the height of the object,
$y = 2.5$	for the height of the lamps,
$z = 4.17$	for the observer's eye height.

The values of r considered are $+1{,}000$, $+500$, $+200$, $+100$, $+50$, 0, -50, -100, r being regarded as positive when the glare source is behind the object. Calculated values for the glare multiplying factor are given in Table 2. These, being independent of the particular beam distributions, may be employed in evaluations of other beam distributions without recalculation.

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Acknowledgment

The work described in this paper was carried out as part of the programme of the Road Research Board of the Department of Scientific and Industrial Research. The paper is published by permission of the Director of Road Research.

A Comparison of Some Common Headlight Beams for Vehicles Meeting on a Straight Road

By V. J. JEHU, M.Sc., A.Inst.P.

Summary

A method of evaluating direct seeing distances, when two vehicles meet on a straight road, has been applied to examples of the two common headlighting systems in current use: one representing British and American practice, and the other representing European practice.

It is shown that the British beam gives better seeing along the nearside road verge, the European beam gives better seeing along the centre of the road, and that straight ahead of the vehicle seeing is about the same with both types of beam. The sharper cut-off European beam is more affected by vertical misaim than the British beam and, when facing one another, seeing with the British beam is improved at the expense of seeing with the European beam.

A comparison of the double-lamp British system with a system in which the meeting beam comes only from the nearside lamp, tilted upward so that its forward horizontal intensity is the same as that from the two lamps, shows that throughout most of the meeting seeing distances are very nearly the same, even when the single lamp faces the double-lamp system. During the later stages of the straight-road meeting, however, recovery from the minimum seeing condition is more rapid when facing the single lamp.

Introduction

Many different solutions to the problem of glare from headlamps have been proposed, but so far as conventional headlighting is concerned two types of beam pattern for the meeting beam are far more commonly used to-day than any others. They are the British or American type of beam, and the European type which has a much sharper and flatter cut-off. Two headlights are almost universally carried, and each produces a driving and a meeting beam. Modern British headlights may be regarded as a variant of the American pattern to suit local conditions.

In a previous paper[1] a method was described by which the seeing distances of small test objects could be evaluated for any meeting beams on a straight road: the method has now been applied to the two common types of meeting beam. The meeting beams considered are the British block lens double-dipping system, representing British and American practice, and a French system representing European practice. A comparison has also been made between single- and double-lamp meeting beams.

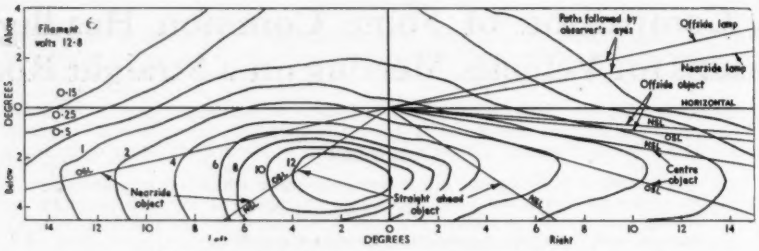
Description of Meeting Beams

The beam distributions chosen to represent the two systems are given in Figs. 1 and 2.

Fig. 1 shows the meeting beam for one British block lens headlamp. It is typical of British and American headlamps, which are aimed by means of the driving beam in relation to which the meeting beams are both dipped and deflected to the nearside.

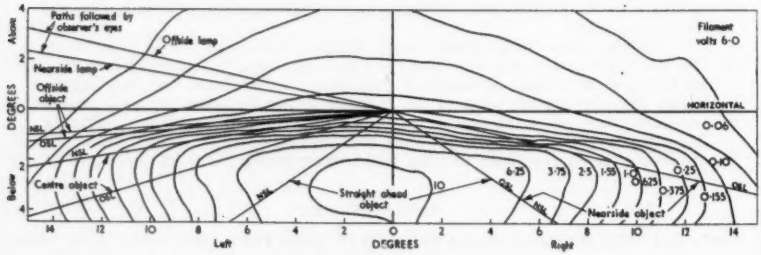
In Fig. 2 is shown the meeting beam from one lamp of the European sharp cut-off system taken from results obtained by KEMA in Holland for the international beam comparisons which were made there in 1949[2]. European lamps are aimed horizontally by means of the driving beams and vertically by means of the horizontal cut-off of the meeting beams, which are not deflected to the nearside in relation to the driving beams. Less light is emitted above the horizontal plane by European meeting beams than by British or American beams.

The author is at the Road Research Laboratory of the Department of Scientific and Industrial Research.
The manuscript of this paper was first received on May 14, 1954, and in final form on September 27, 1954.



Figures to curves denote beam intensity in candelas × 10³
NSL denotes nearside lamp
OSL ,, offside ,,

Fig. 1. Beam distribution from one lamp of the British meeting system.



Figures to curves denote beam intensity in candelas × 10³
NSL denotes nearside lamp
OSL ,, offside ,,

Fig. 2. Beam distribution from one lamp of the European meeting system.

Method of Calculation

The method of evaluating seeing distances for a given meeting beam, facing an oncoming meeting beam, has been described in detail elsewhere[1]. The method is based on experimental data, obtained with beams of uniform intensity, correlating the beam intensity directed at a specified object, the glaring intensity of the opposing lamp, and the distance at which the object was identified, in a standard test situation. To evaluate the seeing distances glaring intensities at specific distances are first evaluated from the beam distribution diagram and the geometry of the test situation. The experimental data is then used to find the beam intensities needed to see the object against the glaring intensities at the various distances. The distance at which the intensity directed at the object becomes as great as that required to see the object against the glare is the distance at which the object will first be recognised. The law that the effect of a glaring light varies inversely as the square of the angular separation between the glare source and the line of sight enables the basic data to be extended to other arrangements of object, observer and opposing lamps, so that seeing distances can be evaluated for any distance between the vehicles.

The situation considered in this paper is that in which two vehicles meet on a 20-ft.-wide road, the lamps of each vehicle being 3 ft. apart (Fig. 3). The height of the lamps above the road is taken as 30 in., the observer's eye height as 50 in., and the seeing distances are those for an object 18 in. high with a luminance factor of 7 per cent.; four object positions across the road have been considered.

Table 1 contains the seeing distances evaluated in the comparison of the British and European meeting beams.

Table 1

Comparison of British and European Meeting Beams

(Seeing distances for an object 18 in. high with a luminance factor of 7 per cent.)

Object position	Distance between object and glare source (ft.)	Seeing distances with the following opposing beams:—					
		British versus British (ft.)	European versus European (ft.)	British $-\frac{1}{2}$ deg. versus British $+\frac{1}{2}$deg. (ft.)	European $-\frac{1}{2}$ deg. versus European $+\frac{1}{2}$ deg. (ft.)	British versus European (ft.)	European versus British (ft.)
Nearside object	+1000	202	158	175	118	220	147
	+ 500	186	151	157	109	210	135
	+ 200	171	141	141	98	198	122
	+ 100	166	136	137	96	193	118
	+ 50	164	134	137	97	190	116
	0	165	132	138	98	188	119
	− 50	171	136	148	106	187	127
	− 100	181	148	164	131	191	150
Straight ahead object	+1000	163	153	138	110	191	133
	+ 500	142	140	117	96	175	117
	+ 200	128	128	108	86	160	104
	+ 100	127	124	108	87	157	103
	+ 50	129	123	111	90	155	105
	0	135	126	114	94	158	111
	− 50	148	135	131	105	166	124
	− 100	166	151	154	131	175	143
Object in centre of road	+1000	163	163	137	120	191	147
	+ 500	129	140	105	97	156	119
	+ 200	91	104	74	73	109	91
	+ 100	71	86	55	61	85	76
	+ 50	59	79	43	53	73	68
	0	84	95	67	67	98	86
	− 50	121	121	104	96	130	114
	− 100	150	147	138	125	160	141
Offside object	+1000	171	151	137	96	176	148
	+ 500	157	147	121	84	170	137
	+ 200	125	131	87	—	149	113
	+ 100	94	108	57	—	120	—
	+ 50	66	—	—	—	92	—

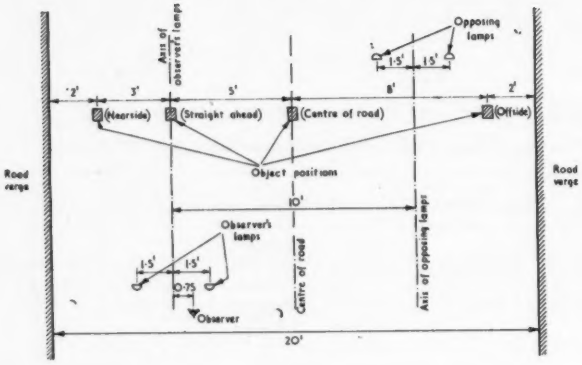


Fig. 3. The assumed arrangement of observer, lamps and object positions on a 20 ft. road.

Like Beams Correctly Aimed

Seeing distance curves for the four object positions obtained with the correctly aimed British system are shown in Fig. 4, from which it will be seen that the value of the minimum seeing distance varies considerably with the position of the object across the road. The low values of seeing distance for objects in the centre and on the offside of the road correspond to circumstances when seeing by silhouette is considerably enhanced owing to the proximity of the glare source to the observer's line of sight. Objects behind the glare source cannot be seen in silhouette, those in front may be. The line dividing the region in which seeing by silhouette is possible, from that in which it is impossible is shown in Fig. 4. The minimum seeing distance with the British lamps for objects on the nearside, straight ahead and in the centre of the road, occurs before this dividing line is reached, i.e., seeing is most difficult when the object is somewhat nearer the observer than the opposing lamps.

The corresponding seeing distance curves for the correctly aimed European system are shown in Fig. 5. Comparison of the two sets of curves shows that with the European system the values of the minimum seeing distance do not vary so much with the position of the object across the road as with the British system. It will also be seen that, with the European system, the minimum seeing distance for the nearside object occurs when the object is at about the same distance from the observer as the opposing lamps; for the other object positions the minimum occurs earlier, as with the British lamps.

The minimum seeing distances for the nearside, straight ahead, and centre of the road objects are 164 ft., 127 ft., and 59 ft. respectively for the British system, and are 132 ft., 123 ft. and 79 ft. for the European system. Thus comparing object positions in the observer's own traffic lane, it appears that the British system gives better seeing for an object on the nearside, the European gives better seeing for an object in the centre of the road, and that the two systems are almost identical as regards straight ahead seeing. It should be remembered that the figures refer only to direct seeing, and that with both systems an object in the centre of the road will in all probability be seen earlier in silhouette.

Vertical Misalignment

The conditions assumed for the foregoing comparison of the two meeting beam systems include a straight level road and correctly aimed beams. Conditions on the road, however, will often be such that one driver will benefit at the expense of the other

This may be due to incorrectly aimed beams, curvature of the road, or slope of the road surface, or to any combination of these three factors.

It is therefore important to consider the effect of misaim on the performance of the meeting beams, and this effect becomes of greater importance in assessing the relative merits of the two systems in view of the fact that it has been shown that there is little to choose between the performance of the correctly aimed beams, at least as far as straight ahead seeing is concerned. The method used to compare correctly aimed beams can equally well be applied to the problem of misalignment.

The particular situation examined is that of an observer using a meeting beam which is aimed ½ deg. too low, looking against an identical meeting beam which is aimed ½ deg. above the correct setting. The procedure adopted is the same as that used for correctly aimed meeting beams, except that the glaring intensities are obtained from a beam pattern which is elevated ½ deg., whilst the beam intensities aimed at the object come from a beam pattern dipped ½ deg. below the correct setting.

The calculated seeing distances for this condition of misaim are included in

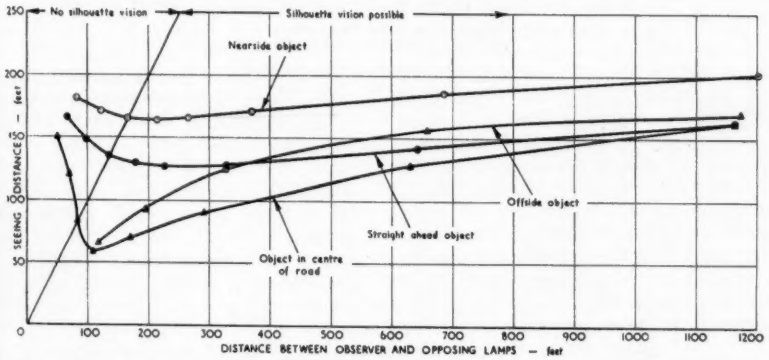


Fig. 4. Direct seeing distance curves for objects on a 20 ft. road with the double-lamp British meeting beam.

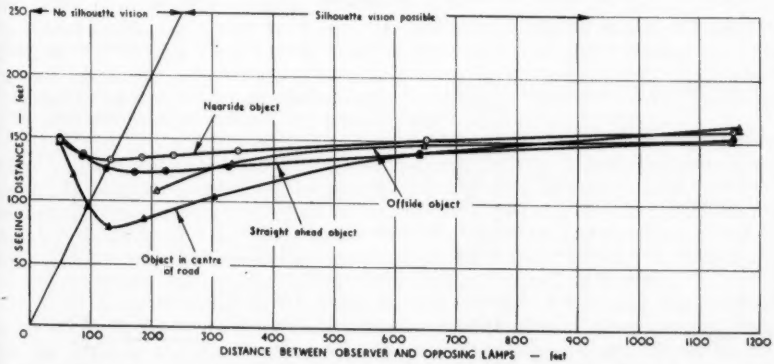


Fig. 5. Direct seeing distance curves for objects on a 20 ft. road with the double-lamp European meeting beam.

Table 1, and the percentage losses in the minimum seeing distances for the incorrectly aimed meeting beam with the greater dip are given in Table 2 for three object positions across the observer's traffic lane. It will be seen that the European meeting beam with its more sharply defined horizontal cut-off is more affected by slight vertical misaim than the British beam. Vertical misaim of $\pm \frac{1}{2}$ deg. is probably the order of accuracy which can be achieved with careful aiming of the beams.

Recently it has been shown that the aim of headlamps in this country is such that beams misaligned by as much as 3 degs. are by no means uncommon[3]. Some account has therefore been taken of the effect of excessive vertical misaim on the performance of the two types of meeting beam by evaluating the seeing distances for an object level with the opposing lamps and straight ahead of the observer's vehicle. The results are given in Table 3, which shows that the adverse effect of vertical misaim is always greater for the European than for the British beam.

Table 2

Minimum Seeing Distances for Similar Meeting Beams Correctly Aimed and also Misaimed $\pm \frac{1}{2}$ degree

Meeting beam	Object position	Minimum seeing distance of object 18 in. high		Percentage loss in seeing distance for beam aimed $\frac{1}{2}$ deg. too low (per cent.)
		Correct alignment (ft.)	Misalignment $\pm\frac{1}{2}$ degree (ft.)	
British	Nearside	164	137	16
	Straight ahead	127	108	15
	Centre of road	59	43	27
European	Nearside	132	96	27
	Straight ahead	123	86	30
	Centre of road	79	53	33

Table 3

The Effect of Vertical Misaim on Seeing Distances

(Object 18 in. high straight ahead of observer's vehicle and level with opposing lamps)

Meeting beam	Aim of beams	Seeing distance (ft.)	Percentage loss in seeing distance due to misaim (per cent.)
British	Correct	135	0
	$\pm\frac{1}{2}$ deg.	114	15
	$\pm$1 deg.	97	28
	$\pm$2 deg.	71	47
	$\pm$3 deg.	50	63
European	Correct	126	0
	$\pm\frac{1}{2}$ deg.	94	25
	$\pm$1 deg.	75	40
	$\pm$2 deg.	52	59
	$\pm$3 deg.	<50	>60

Table 4
Minimum Seeing Distances with Like and Unlike Meeting Beams

Observer's meeting beam	Object position	Minimum seeing distance of object 18 in. high with the following opposing beams:—		Percentage change in seeing distance compared with like opposing beams (per cent.)
		British (ft.)	European (ft.)	
British	Nearside	164	187	+14
	Straight ahead	127	155	+22
	Centre of road	59	73	+24
European	Nearside	116	132	—12
	Straight ahead	103	123	—16
	Centre of road	68	79	—14

Unlike Meeting Beams

A meeting situation which has caused some concern in Europe is that in which drivers use unlike beams, the situation in which one driver uses the European system and the other driver uses American lamps being a common occurrence. To evaluate seeing distances when unlike meeting beams are used, the glaring intensities of one system are coupled with the beam intensities directed at the object by the second system. This has been done for the British and European meeting beams; the calculated seeing distances are given in Table 1, and the percentage changes in minimum seeing distances from those obtained with similar meeting beams are given in Table 4.

When a British beam meets a European beam the minimum seeing distance with the more glaring British beam increases for all object positions in the driver's own traffic lane, from 14 per cent. on the nearside to 24 per cent. for an object in the centre of the road; the minimum seeing distances given by the European beam are correspondingly reduced by from 12 per cent. to 16 per cent.

Single-Lamp Meeting Beam

The method of comparing meeting beams has also been applied to beams other than those from the conventional two-lamp system. A headlamp arrangement which has found favour for a long time in this country, and which is in fact still extensively used, is that in which the driving beam is provided by the two headlamps, but the meeting beam comes from the nearside lamp only. In its simplest form each headlamp produces only one beam, the offside lamp being aimed almost horizontally along the road, and the nearside lamp being permanently dipped to avoid dazzle.

A comparison has been made between the double-lamp and the single-lamp meeting-beam systems, using the beam distribution shown in Fig. 1 in both cases, but with the single nearside lamp raised to give the same glaring intensity straight ahead in a horizontal plane as the correctly aimed double-lamp system. With the particular beam distribution given in Fig. 1 this occurs when the nearside meeting beam is raised 0.8 deg. Glare illumination at the driver's eyes with these settings is almost always somewhat greater for the double-lamp than for the single-lamp system.

The calculated seeing distances for this arrangement of opposing single beams are given in Table 5 and the results are plotted in Fig. 6. The minimum seeing distances for the nearside, straight ahead and centre of the road objects are 177 ft., 141 ft. and 58 ft. for the single-lamp system and 164 ft., 127 ft. and 59 ft. for the normal two-lamp system. Seeing is improved a little throughout the meeting for the nearside and straight

Table 5

Comparison of Single- and Double-Lamp Systems

(Seeing distances for an object 18 in. high, with a luminance factor of 7 per cent.)

Object position	Distance between object and glare source (ft.)	Seeing distances with the following opposing beams :—			
		Double lamps versus double lamps (ft.)	Single nearside lamp raised 0.8 deg. versus Single nearside lamp raised 0.8 deg. (ft.)	Double lamps versus single lamp (ft.)	Single lamp versus double lamps (ft.)
Nearside object	+1000	202	209	205	204
	+ 500	186	194	192	188
	+ 200	171	181	179	171
	+ 100	166	177	176	166
	+ 50	164	178	177	164
	0	165	180	179	166
	— 50	171	188	187	171
	— 100	181	200	198	181
Straight ahead object	+1000	163	170	168	166
	+ 500	142	151	149	143
	+ 200	128	141	140	128
	+ 100	127	143	142	127
	+ 50	129	147	146	129
	0	135	156	154	135
	— 50	148	170	168	150
	— 100	166	187	184	168
Object in centre of road	+1000	163	161	166	159
	+ 500	129	122	128	123
	+ 200	91	79	88	83
	+ 100	71	61	74	58
	+ 50	59	64	84	<50
	0	84	108	116	72
	— 50	121	140	145	116
	— 100	150	169	173	147
Offside object	+1000	171	167	171	168
	+ 500	157	154	158	154
	+ 200	125	119	124	119
	+ 100	94	81	93	—
	+ 50	66	—	—	—

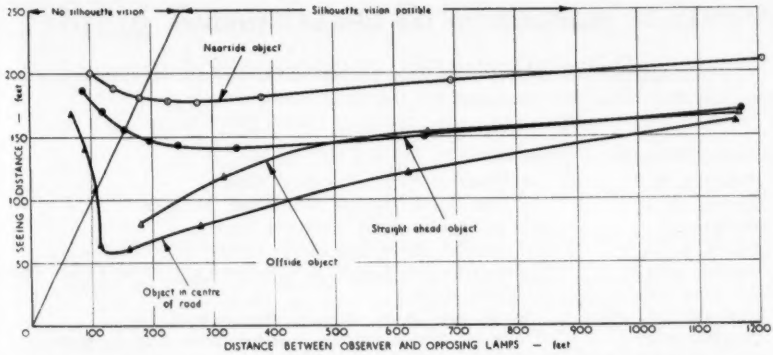


Fig. 6. Direct seeing distance curves for objects on a 20 ft. road with a single-lamp British meeting beam.

ahead objects. Direct seeing for the object in the centre of the road is somewhat worse than that with the two-lamp system in the early stages of the meeting, although the minimum seeing distance is about the same.

The most noticeable difference between the single- and double-lamp systems occurs during the later stages of the meeting, when the opposing vehicles are comparatively close together. In these circumstances the rise from the minimum seeing distance for all three object positions in the driver's own lane is more rapid with the single- than with the double-lamp system.

A common situation on the roads in this country at present is that in which the single-lamp system meets the double lamps. The seeing distances evaluated for this straight road meeting are included in Table 5. Again the most important differences from the situations in which like beams meet occur during the later stages of the encounter, seeing with the double-lamp system being improved at the expense of that with the single-lamp system.

It appears therefore that when vehicles with properly aimed headlamps meet on a fairly narrow straight road, two lamps are not better than one. This is not to say that two lamps are never an improvement on one. It is undeniable, for example, that the extra illumination across the road from two lamps is better for the driver behind the lamps; it is also true to say that the chance of seeing an object in silhouette against two lamps is greater than that against one lamp.

Conclusion

The characteristics of various types of meeting beam in common use have been determined for the situation in which two vehicles meet on a fairly narrow straight road.

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(2) Nederlandse Stichting voor Verlichtingskunde. International visibility tests with motor-car lighting carried out at Zandvoort (Holland) in October, 1949, in accordance with the resolution of the Committee 23b of the "International Committee on Illumination" at the Congress held in Paris in 1948.

(3) Jehu, V. J. A Survey of Vehicle Headlights. Trans. Illum. Eng. Soc. (London), **18**, 249-59 (1953).

Additions to the List of Members

The following applicants have been duly elected by the Council to membership in the Society and their names have been added to the list of members:—

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Lighting Design and Brightness Patterns—a Preliminary Investigation

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Summary

While almost every aspect of lighting design for the whole visual field has been studied and much data accumulated, no single comprehensive method of design making full use of this work has been evolved.

The purpose of this paper is to describe an investigation made with the object of devising a method of lighting design in which the type, number and arrangement of fittings are determined from a consideration of the illumination and brightness patterns required at all surfaces in a lighted interior.

The chief factors to be considered when designing a lighting installation are presented and an analysis made of the present state of knowledge and practice. Use of the sector flux method of direct illumination calculation for linear sources has been checked and extended, a method of measuring and expressing the ratio of the direct to total illumination at any point in a room is described, and the assessment of glare is considered. These factors, direct lighting calculation, the Building Research Station glare data, and an experimentally determined inter-reflection ratio are combined, leading to the proposition of a new design method which takes account of the brightness pattern on all surfaces affecting an interior lighting design.

(1) Introduction

The conception of interior lighting has recently undergone a considerable change. Lighting engineers are becoming more aware of the complex nature of the mechanism of interior lighting, knowing something of how its various elements contribute to the formation of the final integrated design which is a combination of psychological and physical factors.

These factors, which include light for the task, emphasis and contrast, adaptation of the eye, the nature of the general surroundings including comfort and distraction, revelation of form and architecture, inter-reflection, colour and decorations, have all been studied, and whilst some of them are primarily the province of the architect, the lighting engineer must understand them all. Knowing these factors and understanding the interplay of one with another, however, is not enough; the practising lighting engineer must be able to put any desired combination of them into concrete form.

Before this can be accomplished it is necessary to express quantitatively the combined effect of these factors in terms of illumination, luminance and colour, and it is here that difficulty has been experienced. The problem as a whole has not hitherto been clearly analysed and stated so that gaps in our knowledge could be bridged by further investigation, thus allowing for the development of a more comprehensive method of lighting design.*

Most lighting problems could be solved by using methods derived from fundamental considerations, but this would be laborious and take an enormous amount of

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* Since the preparation of this paper was begun the matter has been dealt with in detail. See Ref.(13).

time which in many cases could not be justified. A simple method of solving these problems, which can be easily understood and used, is required.

In the past we have depended upon the lumen method of design as developed by Harrison and Anderson, knowing its limitations which have increased with the widespread use of fluorescent lighting. In America, Moon and Spencer modified and extended the lumen method by the introduction of inter-reflection data(1), and this has been simplified to some extent by the Quality and Quantity Committee of the American I.E.S. Harrison and Meaker with glare factors(2) (3), Luckiesh and Guth with borderline between comfort and discomfort (B.C.D.)(4) (5) (6), Logan on the basis of natural lighting(7), Petherbridge and Hopkinson(8) (9), Vermeulen and de Boer(10) have all contributed to a more satisfactory approach, but inaccuracies and complications remain to be resolved.

For several years lighting engineers in this country have been considering and discussing how best to overcome this difficulty, but without very much real progress. With this in mind the authors decided to investigate the possibility of finding some new approach to lighting design which would include the brightness pattern throughout the whole of the visual field.

The intention was to look into known methods of lighting calculation to see which of them could be extended to the whole of the visual field with reasonable accuracy combined with simplicity.

In analysing the problem the conclusion was reached that it was essential to be able to specify the required brightness patterns quantitatively, and from this to determine the illumination at any point of the room necessary for the production of the desired brightness pattern. This illumination would then need to be separated into its two components, direct and inter-reflected light.

It is upon this basis that a new method of design has been attempted which will apply to installations where the formation of definite brightness patterns is important, such as commercial and industrial interiors, drawing offices, restaurants, assembly rooms and schools. Where the conditions of the lighted interior are such that inter-reflections are small and atmospheric absorption high, e.g., steel mills or foundries, the method as a whole would not apply. The lighting design of most domestic interiors, and rooms where the flux distribution and brightness patterns are very complex, must remain empirical as it is not easily accomplished by engineering methods.

(2) Outline of Proposed Design Method

As already pointed out the problem can be divided into three main sections :—

(a) Specification of brightness pattern.
(b) Direct lighting component.
(c) Inter-reflected light.

These can now be sub-divided, as follows, to show step-by-step the outline of the proposed method, reference being made to the relevant sections :—

Stage (1). Draw up a specification of the required brightness pattern. (Section 3.)

Stage (2). Select the lighting fitting considered suitable for the task. (Section 4.)

Stage (3). From Stage (1) calculate the direct illumination to all relevant parts of the room, making use of the inter-reflection data. (Sections 6 and 7.)

Stage (4). By multiplying direct illumination by the respective areas, determine the total direct flux required to illuminate the room, and from a knowledge of the light output ratio determine the total number of fittings.

Stage (5). From a knowledge of the structural form of the building and from aesthetic considerations, decide upon the number of rows of fittings.

Stage (6). Using the value of illumination specified for the task, calculate the number of fittings per row. (Section 6.)

Stage (7). Check the glare condition using $K = \frac{B_s^2 \omega}{B_b}$ (Section 5.)

Stage (8). Finally, if desired, the illumination and luminance at any point can be calculated.

Stage (9). Design any local lighting required.

The major factors involved in the proposed design method are discussed in the following sections.

(3) Specifying the Brightness Pattern

It is desirable to state the chief function of brightness patterns in rooms and to see where recommendations can be made which will assist in fixing numerical values to the specification envisaged by the designer. A detailed analysis of brightness patterns suitable for all rooms, activities and aesthetic effects is outside the scope of this paper[11] [12] [13] [14]. Only the chief purposes of the brightness pattern will therefore be considered. These are :—

(1) To reveal the chief object of interest in a manner consistent with visual ease.
(2) To grade the brightness over the major surfaces of the room so that there are no violent contrasts which might cause discomfort or distraction.
(3) To create centres of secondary interest and visual rest centres.
(4) To avoid monotony by the use of modelling to reveal texture and form and to indicate divisions of architectural surfaces.

Colour comes into play in all these things and must be considered when reflection factors of surfaces are being specified. In the Ministry of Education Bulletin No. 9, Colour in Schools, we are shown the importance of planning colour and reflection factors at an early design stage, and this should be done for both natural and artificial lighting.

From a consideration of the purpose of a room the brightness pattern can be related either to the illumination required for the chief room activity, where a specific task has to be performed and visual efficiency and comfort are equally important, or to the structure, contents and furnishings of a room where aesthetic effects or display are the chief considerations.

Where the illumination for the task is of the first importance, the amount can be determined using the method set out in the I.E.S. Code (1949) pp. 13-17. Since in this case the visual task remains the chief centre of interest, its brightness should be greatest and its immediate surround less bright, the degree of change being determined by size, colour and contrast in the task itself.

It has been shown[12] that this grading of brightness from the task outwards should continue to the main surfaces of the room which generally determine the adaptation level of the eye. The ratio of the luminance of the task to its surroundings which will provide ease of seeing with freedom from discomfort will vary with the task. In America a 3 to 1 ratio for the brightness of the task to its immediate surround and a 3 to 1 ratio for the brightness of the immediate surround to that of the general surround has been used as a guide in a wide variety of installation designs, but studies made at the Building Research Station[8] and experience indicate that this ratio is generally too narrow and inflexible, and that an overall ratio as high as 50 to 1 can be quite acceptable in some cases. The choice of a suitable ratio can at present only be left to a joint decision of the interior designer and lighting engineer, but perhaps with greater experience and the collection of suitable data over a period of time, some guidance in the form of a code of practice may be prepared to help the lighting engineer. This code need only suggest limits to avoid discomfort due to glare.

The other major factor in specifying a brightness pattern is the relationship between the brightness of the lighting fitting and its immediate surround, and the general surroundings. In this regard it is suggested that the Building Research Station data[9] and modified glare formula[15] can be used quite satisfactorily (see Section 5).

Finally, there remain to be considered the areas of interest, visual rest centres,

modelling and the spatial divisions of structural surfaces which in particular will be closely associated with colour, and the direction of light. The important factor to remember is that if great brightness contrasts are desired then the area must not be so great as to modify the general adaptation level appreciably, or to cause unwanted distraction.

In specifying the brightness patterns, it is suggested that the following plan would help in arriving at decisions on the various luminance values required :—

(1) Determine the illumination for the task.
(2) Decide upon a suitable luminance for the immediate surround to the task and its reflection factor.
(3) Decide upon a glare condition which is acceptable for the task in hand or purpose of the room.
(4) From a consideration of the accepted glare condition and the luminance of fittings available, decide upon the average luminance and reflection factors of walls, ceiling and floor.
(5) Decide upon luminance and reflection factor of surfaces where modelling is required, and also for those surfaces which are intended as visual rest centres.

Directional lighting, if required, should also be specified alongside the luminance values for areas thus illuminated.

(4) Selection of Lighting Fitting

Having drawn up the brightness pattern specification the problem arises as to how to choose a suitable fitting. From the brightness pattern the desired light flux to each surface will be known (taking into account inter-reflections, see Section 7), and can be expressed as flux in specified angular zones. If information on the flux from fittings in these zones were available the choice of fitting would be facilitated, but it must be emphasised that this would act only as a rough guide, since the intensity distribution from a number of rows of fittings is similar in shape but not identical to that from a single fitting.

Other factors to consider when choosing a fitting are its appearance and the way it merges with or is appropriate to its surround. The light output ratio, although important, should not be given undue priority, for comfort must take precedence over "fitting efficiency" and accurate control of distribution and brightness cannot be obtained without some loss of light.

The recommended luminance of fittings will vary according to location and the amount of brightness grading possible, but 2½ candles per sq. in. should be taken as a maximum for any fitting within 45 deg. of the line of sight. This applies for surround luminance values up to 10 ft.-lamberts.

It will be seen from the above that adequate photometric data must be available. This data should include intensity distribution curves in the plane of the axis of the fitting and in that normal to it, the light output ratio and the luminance of the main areas of the fitting. Further useful information would be the polar distribution of sector flux, calculated for the particular fitting, and total flux in selected zones.

The present position in this country is that a few manufacturers provide some technical information on their fittings and many provide none at all. In many cases the expense of test equipment is the chief deterrent.

(5) Prevention of Glare

An essential prerequisite for specifying the brightness pattern is an understanding of the inter-relation of the various factors affecting glare. The principal researches on this subject have been undertaken in the United States(2) (4), the Netherlands(10) and in this country(8) (9). Comparison of the results, taking into account the differences in the experimental techniques, shows sufficient similarity to justify the use of

a single modified glare formula as suggested by the Building Research Station[15]. In the authors' opinions the soundest approach is to use this formula as an indication of the glare condition, but also to be conversant with the following findings which are extracted from the Petherbridge and Hopkinson paper :—

(1) Increase in the size of a source of high luminance will have greater effect on glare than the same proportional increase in the size of a source of low luminance.

(2) Increase in luminance of a large bright source will have a greater effect on glare than the same proportional increase in luminance of a small source.

(3) The glare effect from a number of sources within 45 deg. or at most 50 deg. of the line of sight can be taken as additive, and sources at greater angles may be neglected, for their effect on discomfort is slight. However, bright sources beyond 45 deg., although not uncomfortable, may be distracting.

(4) The glare effect from a number of sources of equal luminance is the same as that from a single source of equal apparent area.

(5) As the luminance of the intermediate surround to a glare source is increased beyond that of the general surround, the glare is first reduced and then increased as the intermediate surround becomes an additional glare source. The maximum reduction in glare occurs when the luminance of the immediate surround lies between that of the general surround and that of the source, but if conditions are acceptable, grading the surround proves of little or no value.

(6) A modified glare formula[15] has been derived which is restricted to *interior* lighting conditions. Glare constant $K = \frac{B_s^2 \omega}{B_b}$

where B_s = luminance of source (foot lamberts)
B_b = luminance of background (foot lamberts)
ω = angular subtense of source (steradian).

The values obtained from this formula are best interpreted from the following table :—

K	Criterion of discomfort (condition of no visual task)
3,000	Just intolerable
3,000–600	Uncomfortable but not intolerable
600	Just uncomfortable
600–120	Distracting but not uncomfortable
120	Just acceptable
120–24	Acceptable but not imperceptible
24	Just imperceptible

(6) Calculation of Direct Light

The direct illumination from point sources at any point can be found with relative ease, though where a large number are present the process may be laborious.

Dealing with rows of fittings whether using fluorescent or tungsten sources gives rise to two major difficulties. Firstly, sources have widely differing polar distributions and secondly, they are in the majority of cases three dimensional in form.

A number of possible methods which would enable illumination from three dimensional sources to be calculated for points in any plane have been investigated, and it was concluded that no single simple method could be applied to all conditions. Consequently, a method which gives reasonable accuracy over a large range of conditions must be accepted. The conclusion has therefore been reached that application of

the sector flux method proposed by Einhorn[16] will lead to the smallest errors consistent with simplicity, because the variation in polar distributions is taken into account and, for sources which are long compared to their other dimensions, errors due to width and depth are small for all points not too near the fitting.

Einhorn's paper may be summarised as follows:—

Sector flux (J) is defined as flux per unit length per unit angle. The illumination on a surface parallel to a long linear source is $\frac{\text{sector flux}}{\text{distance}}$ x (cosine of the angle between the normal and the line joining the source to the surface) i.e.,

$$E = \frac{J}{R} . \cos\theta$$

Where I_0 is the intensity per foot at the downward vertical, the relation between J and I_0 is a constant *for any particular fitting*, and is an indication of the shape of the axial polar distribution.

The paper includes curves which enable the illumination from installations of finite length to be calculated with facility for vertical or horizontal surfaces, i.e., illumination under a finite source = illumination under an infinite source x $(1 - \Delta)$, where Δ is the fraction of the illumination lost owing to the ends of the source being at a finite distance.

Having applied this method to practical installations and investigated its range

Table 1

Key Letter	Description	J/I_0 Factor
X	Constant Intensity	2.00
Y	Cosine Distribution	1.57
Z	Cosine^2 Distribution	1.33
A	Matt Reflector	1.61
B	Specular Reflector	1.47
C	Flush Mounted 040 Perspex	1.44
D	Louvred with Perspex Sides	1.38
E	Flush Mounted Deep Louvres	1.12

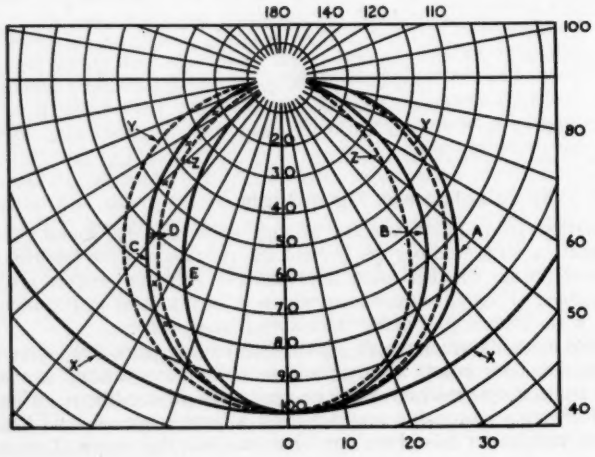


Fig. 1. Measured axial intensity distributions and J/I_0 factors used in sector flux calculations for a range of practical linear light sources.

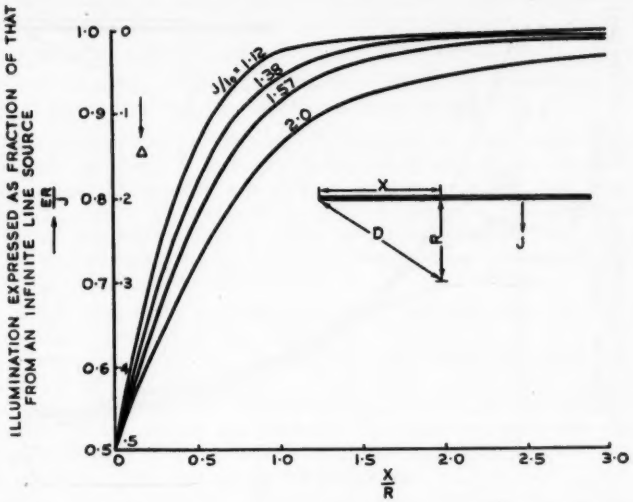


Fig. 2. Illumination from a finite linear source on a surface parallel to the lamp axis.

of applicability, it is found to be both reasonably simple and accurate. Polar curves in the plane of the axis of the source and in the plane normal to it, as published by some manufacturers, provide sufficient data for its application.

A number of practical fittings have been photometered and an analysis made of the relationship between the shape of the polar curves and the J/I_0 factor. It was found that the polar curve of intensity (or intensity/foot) in the plane through the axis of the source is directly related to the J/I_0 factor, as might be expected from theoretical considerations. Some of these curves and J/I_0 factors are shown in Fig. 1 and Table I, and should enable the lighting engineer to estimate the value of this factor for any fitting under consideration. The fall-off in illumination due to the ends of sources is shown in Fig. 2 and Fig. 3, which have been derived from measured data on the above-mentioned practical fittings. They agree well with Einhorn's theoretical curves but, covering a rather wider range, should prove of value.

The following points are derived from experience with the method, and photometry of fittings:—

(1) If the radial distance of the point from the source (R) is less than five times the effective width of the source, the source cannot be considered linear and errors in excess of 10 per cent. will occur.

(2) The theory as at present developed applies only to sources with an axial distribution such that the maximum intensity occurs at the downward vertical.

(3) Errors may occur when calculating the illumination on surfaces near to the source, and particularly on vertical surfaces normal to its axis due to width and depth dimensions becoming relatively important.

(4) The set of curves Fig. 2 applies for all planes parallel to the lamp axis, i.e., floor and side walls.

(5) The *shape* of the polar distribution in the plane through the axis is effectively the same for all such planes.

(6) The J/I_0 factor, in addition to its use in the sector flux method, is a useful means of specifying the shape of the polar distribution from a source in its major axis and has been used for this purpose throughout the paper.

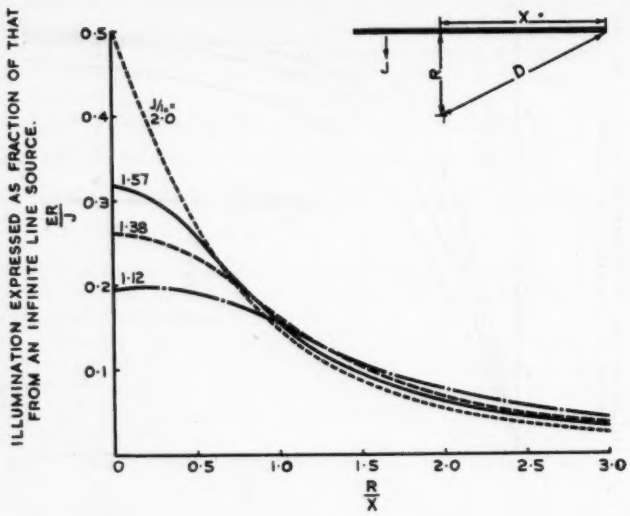


Fig. 3. Illumination from a finite linear source on a surface normal to the lamp axis.

(6.1) Illumination on the Work Plane

The design method proposed arrives at the total number of fittings and the rows in which they are arranged from a consideration of the brightness pattern. The illumination on the working plane remains important, however, and has to be considered. This is done in the following manner. Accepting the number of rows of fittings as decided, take the central point in the room and the required direct illumination (E_d) at that point then becomes $E=\frac{J}{R}\cos\theta$ and the sector flux at any point $J=\frac{I\times(J/I_0)}{C}$ (where C is the spacing between centres of fittings).

Therefore:

$$E_d=\frac{I_1\times J/I_0}{C\times R_1}\cos\theta_1\,(1-\Delta_{a1}-\Delta_{b1})+\frac{I_2\times J/I_0}{C\times R_2}\cos\theta_2\,(1-\Delta_{a2}-\Delta_{b2})\quad\ldots\ldots\ldots\ldots\ldots(1)$$

where suffix 1, 2, etc., refers to rows No. 1, 2, etc., and suffix a and b refer to the end of the source considered.

The factor $(1-\Delta)=\frac{ER}{J}$ where the illuminated plane is normal to the incident light, may be obtained from Figs. 2 and 3, and C is the only unknown. Hence we have the spacing per row.

A compromise may be necessary between the requirements of the general brightness pattern and that of the working plane illumination, i.e., it may not always be possible to find the ideal fitting.

(7) Calculation of Inter-reflected Light

Little work has been done in the last five years on inter-reflections. In 1946 comprehensive tables were prepared by Moon and Spencer [1] [17], based upon the theoretical work of Buckley[18], and presented in simplified form by the Quantity and Quality Committee of the American I.E.S. [19] [20]. These tables enabled the total amount of

light including inter-reflections to be derived for various surfaces. There are, however, practical difficulties in the way of applying them to a lighting design:—

(1) They are not suitable for point by point application, being averages for a surface.

(2) They require a knowledge of the amount of light flux falling on each surface, determination of which is a laborious process in most instances.

(3) Though it is relatively simple, by this method, to obtain the final luminance of a surface knowing the direct illumination falling on it, the reverse procedure, i.e., deriving the direct illumination necessary to produce a specified final luminance, is extremely complex. (It is possible to derive a formula to give the desired results, but it is so long and requires so many ratios to be obtained from tables, each of which usually necessitates one or more interpolations between the published figures, that its use is quite impractical.)

In the form in which these tables are presented in the American I.E.S. Handbook (2nd Edition), difficulty (2) above has been overcome, but (1) and (3) still apply. Furthermore, until experimental work is done to check their theoretical values for a wide range of practical conditions, some doubt will remain as to the amount of error involved in the basic assumption of perfectly diffusing room surfaces. In the course of the present investigation an attempt was made by the authors to overcome these difficulties from a consideration of fundamental theoretical principles, but a method simple enough for practical application could not be found.

It seemed therefore that an empirical method might help to clarify the position, and with this intention a model technique was evolved. It had been found that the easiest means of obtaining a precise knowledge of the total illumination to be expected in specific installations was to build a model and find the ratio of direct illumination to total. This process had been successfully applied to a number of intricate designs. To apply this technique generally to all designs was therefore a logical development and it was decided to measure a single ratio E_{total}/E_{direct} or E_t/E_d which would

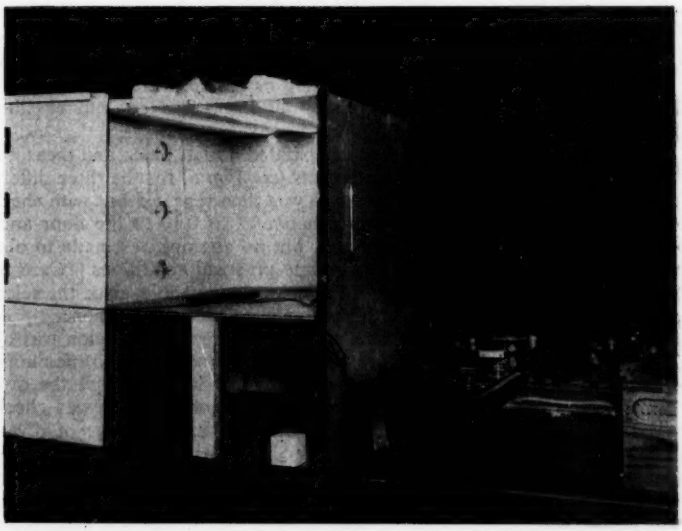


Fig. 4. Apparatus used in determination of the inter-reflection ratio.

be very simple to handle. The usefulness of such a ratio will be seen from the fact that $\frac{E_t}{E_d} = \frac{E_i + E_d}{E_d}$ from which E_i (the inter-reflected component) could be obtained.

In such an investigation there are three major variables to be considered :—

(1) Polar distribution of fitting.
(2) Shape of room (room index).
(3) Surface reflection factors.

(7.1) Determination of the Inter-reflection Ratio

For this preliminary study the surface reflection factors (ρ) were kept constant, the polar distribution of fittings and the room index were varied. The following values of ρ were chosen as being those most frequently found in practice :—

Ceiling $\rho = 0.75$
Walls $\rho = 0.50$
Floor $\rho = 0.10$

The room index was calculated from the formula

$$K_r = \frac{h\ (w + l)}{2wl}$$

where h, w and l are height, width and length respectively.

This formula was developed by Hisano[21] and he has shown both theoretically and experimentally that it applies for $K_r \leqq 2$ and for $\frac{l}{w} \leqq 4$ with an error of less than 10 per cent. These limitations apply to the $\frac{E_t}{E_d}$ ratio as they do to the Moon and Spencer tables, but most practical installations will fall within the above limits.

The equipment (see Fig. 4) consisted of a 2-feet cubic model room or box, with a movable floor which enables the room index to be altered. A removable end wall and a side wall were fitted with shuttered windows for the insertion of the cosine corrected cell[22], which was used for all measurements. Three ¼-in. wide slots ran the full length of the ceiling for mounting the line sources. These sources (see Fig. 5) were of three widely differing polar distributions :—

(1) Row of silica coated tungsten filament lamps (constant intensity distribution*).
(2) Strips of ⅛ in. (type 040) diffusing " Perspex " lit by 2-ft. 40-watt fluorescent lamps (approximately uniformly diffusing or cosine distribution*).
(3) Edge-lit ¼ in. clear " Perspex " fitted with deep louvres illuminated as (2) (approx. $\cos^3$ radiator*).

The interior of the apparatus was painted a matt black and measurements of direct illumination taken at a number of points (see Fig. 6) for the three different sources and for three room ratios. This procedure was then repeated but with sheets of cardboard of 0.50 reflection factor attached to the walls, of 0.10 to the floor and of 0.75 to the ceiling. These sheets were fairly matt but no attempt was made to obtain really matt surfaces, as the intention was to simulate practical conditions. Care was taken, however, to have the surfaces as neutral in colour as possible, since the selective absorption of coloured surfaces would further complicate the investigation.

From the above tests the ratio of total to direct illumination was obtained.

In all tests the number of rows of fittings was varied to maintain fairly uniform illumination across the measuring points on the floor, so that the diversity ratio for these points was never below 0.70. The effect of diversity was checked by altering the number of fittings for one room index, causing a change of diversity ratio from 0.85 to 0.50 and E_t/E_d was found to vary by less than 4 per cent.

The E_t/E_d ratios have been obtained as accurately as possible within the limitations

* The description of the polar distributions in brackets above refer to that in a plane through the axis of the source.

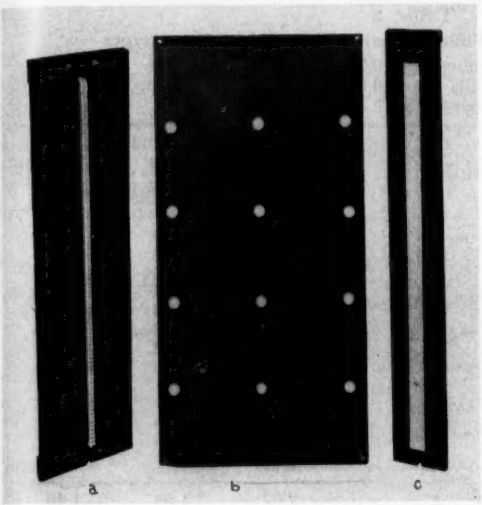


Fig. 5. (Left) Model fittings used in inter-reflection tests.
(a) Louvred source, cos³ radiator.
(b) Tungsten incandescent, constant intensity source.
(c) Diffusing source, cos radiator.

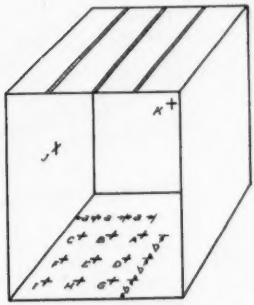


Fig. 6. (Right) Diagram showing position of test points used in inter-reflection ratio measurements.

of the apparatus and errors greater than ± 10 per cent. should not occur. The projected wider investigation will include a variety of reflection factors and some refinements in technique in order to achieve an order of accuracy of ± 5 per cent. Work is under way for dealing with the question of the ceiling. Some of the difficulties which it presents both for assessing the amount of direct and of inter-reflected illumination have been solved, but some remain to be overcome. Where no direct light falls on a surface it is proposed that the ratio be expressed as E_t/E_d (working plane) for all such points considered. This is not likely to occur frequently in the type of installation where this method would be applied.

Comparisons for similar conditions with the Moon and Spencer inter-reflection tables have shown a maximum discrepancy of 10 per cent. It is too early to state on which side the errors occur, but it will be seen that by using the E_t/E_d ratio it is possible, having specified the total luminance and knowing the reflection factors of all surfaces, to derive simply the direct illumination required at all points.

(7.2) Results

The inter-reflection ratios for the series of tests so far undertaken are shown in Table 2, and are plotted against room index Kr for each of three sources in Fig. 7.

Fig. 8 shows the relation between the inter-reflection ratio and source distribution for three room indices Kr = 1.12, 0.66 and 0.22.

For any one condition of room shape, reflection factor, and source distribution, it will be seen that the E_t/E_d ratios remain reasonably constant for various floor positions. Therefore judging from the range of conditions investigated, it would appear that where the illumination is fairly uniform, an average floor ratio should be adequate for most practical purposes. The curves in Figs. 7 and 8 have been plotted on this assumption. It should be noted that though these ratios remain constant the absolute values will vary from point to point depending upon the direct light incident at the point.

Table 2

Experimentally determined inter-reflection data for three source types

Ceiling $\rho = 0.75$
Walls $\rho = 0.5$
Floor $\rho = 0.1$

	Position	Room Index 1.12	0.66	0.22
		Inter-reflection Ratio E_t/E_d		
Point sources $\frac{J}{I_o} = 2.0$	Floor A	3.60	2.69	1.65
	B	3.62	2.76	1.58
	C	3.66	2.76	1.72
	D	3.52	2.75	1.51
	E	3.53	2.80	1.50
	F	3.53	2.88	1.40
	G	3.62	2.76	1.60
	H	3.50	2.80	1.74
	I	3.61	2.81	1.67
	Floor Average	3.58	2.77	1.59
	J	2.86	2.13	1.55
	K	2.77	2.06	1.66
	Wall Average	2.81	2.09	1.60
Diffusing sources $\frac{J}{I_o} = 1.57$	Floor A	2.07	1.59	1.46
	B	2.06	1.64	1.39
	C	2.10	1.63	1.36
	D	2.08	1.65	1.50
	E	2.10	1.65	1.49
	F	2.13	1.69	1.50
	G	2.15	1.68	1.46
	H	2.16	1.76	1.59
	I	2.16	1.73	1.36
	Floor Average	2.11	1.67	1.46
	J	1.99	1.56	1.68
	K	2.00	1.80	1.74
	Wall Average	2.00	1.68	1.71
Louvred sources $\frac{J}{I_o} = 1.11$	Floor A	1.34	1.21	1.18
	B	1.29	1.21	1.17
	C	1.42	1.25	1.04
	D	1.39	1.27	1.23
	E	1.33	1.25	1.23
	F	1.40	1.20	1.06
	G	1.41	1.31	1.18
	H	1.39	1.31	1.16
	I	1.50	1.33	1.10
	Floor Average	1.38	1.26	1.15
	J	1.66	1.52	1.61
	K	1.78	1.72	1.63
	Wall Average	1.72	1.62	1.62

(8) Application of Method to School Classroom

The foregoing method has been applied to a practical example to illustrate its application. The room is 30 ft. long x 22 ft. wide and ceiling height 11 ft. 6 in.; the room has a large window in one side wall positioned as in Fig. 9. This window will be fitted with venetian blinds of the same reflection factor as the walls, which will be lowered to their full extent during periods when artificial lighting is used.

The classroom is one in which daytime and evening classes are held, activities being reading and writing, thus visual performance and comfort must be good.

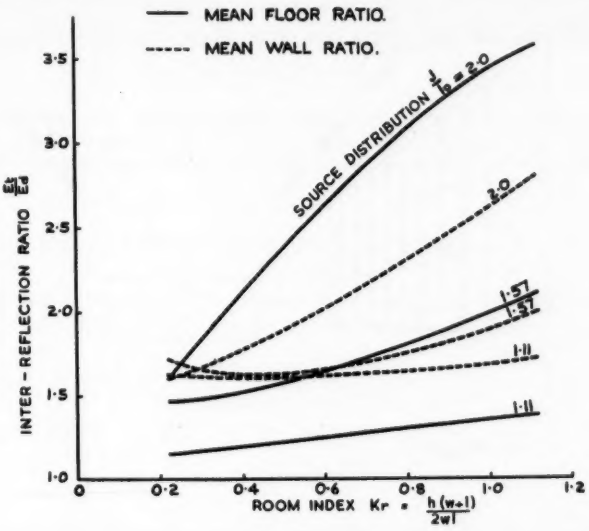


Fig. 7. Curves showing the relation between the inter-reflection ratio and room index for three different source distributions.

Stage (1).

From the I.E.S. Code minimum illumination for the task should be 15 lm./ft.^{2}, and therefore to ensure adequate illumination 20 lm./ft.^{2} will be used. Reflection factor of good quality white paper is 0.80. Thus the luminance of the task will be 16 ft.-lamberts.

The immediate surround to the task will be almost entirely the table tops, and if these are in light natural finish wood the reflection factor will be approximately

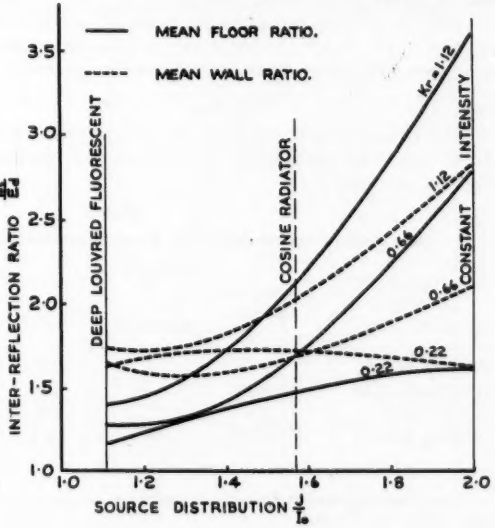


Fig. 8. Curves showing the relation between the inter-reflection ratio and source distribution for values of room index from 1.1 to 2.0.

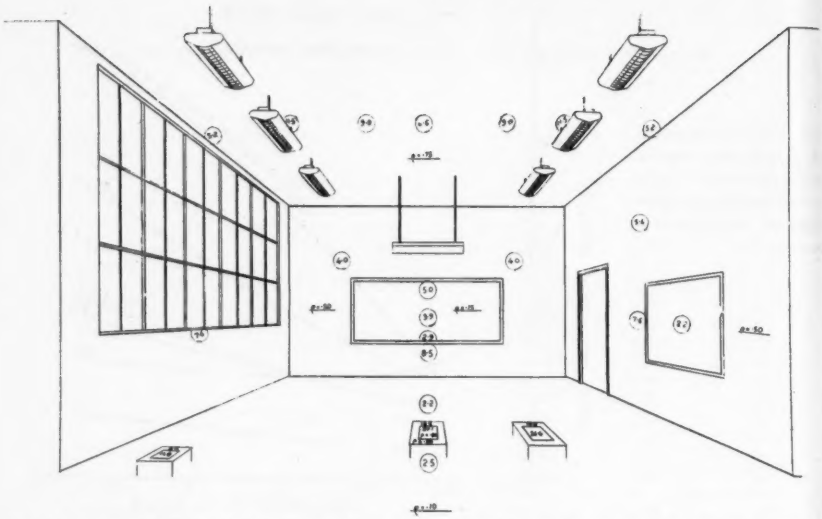


Fig. 9. Perspective view of classroom, showing surface reflection factors and luminance values in ft.-lamberts at various positions in the room.

0.50 and the luminance 10 ft.-lamberts. For comfortable seeing conditions the visual field should be graded outwards and an adaptation brightness or general surround luminance of 8 ft.-lamberts chosen.

Considering now an acceptable glare condition, a glare constant of 120 (Building Research Station new glare formula) or smaller will be the aim, i.e., between just imperceptible and just acceptable.

Let the average reflection factors of the walls be 0.5, of the ceiling 0.75, and of the floor 0.10, which conform to the inter-reflection tests here presented and at the same time are values frequently found in practice.

Stage (2).

The choice of a fitting is at the present time limited, and with the above information in mind and particularly the principle of brightness grading, the fitting shown in Fig. 9 was chosen.

Table 3

Data used in determination of direct illumination and flux on room surfaces

Surface area sq. ft.	Reflection factor ρ	Luminance B ft.-lamberts	Total Ill. E_t lm/ft.²	Inter-reflection ratio E_t/E_d	Direct Illum. E_d lm./ft.²	Flux lm.
Side walls, 690	0.5	9	18	1.60	11.25	7,760
End walls, 506	0.5	9	18	1.60	11.25	5,690
Floor, 660	0.1	2	20	1.35	13.30	8,760
Ceiling, 660	0.75	10	13.3	1.90	7.0	4,630
					TOTAL ...	26,840

Room Index Kr=0.453.

Stage (3).

The direct illumination required on walls, floor, and ceiling and the total flux is given in Table 3.

Stage (4).

From Table III the total flux required to all room surfaces is 26,840 lumens. With the fitting chosen a light output ratio of 0.6, a maintenance factor of 0.85 and lamp flux per fitting 6,400 lumens, eight fittings will be required to satisfy the brightness specification.

Stage (5).

From a consideration of room size two rows of fittings will be used.

Stage (6).

E_t (average) is required to be 20 lm./ft.^{2}. As this is an average value 23 lm./ft.^{2} will be necessary at the centre point in the room for a diversity ratio of 0.7.

For the classroom floor

$$\frac{E_t}{E_d} = 1.35 \quad \therefore E_d = \frac{23}{1.35} = 17 \text{ lm./ft.}^2.$$

$$\frac{X}{R} = \frac{15.00}{9.3} = 1.61 \quad \therefore \Delta_a = 0.02 = \Delta_b \text{ (from Fig. 2)}$$

$$1 - \Delta_a - \Delta_b = 0.96$$

From Fig. 10 intensity from one row = 865 cd. Cos $\theta = 0.806$ $\frac{J}{I_0} = 1.38$ R = 9.3

$$\therefore \text{ from Equation 1 (page 86) } 17 = 2 \times \frac{865 \times 1.38}{C \times 9.3}(0.96)\ 0.806$$

$$\therefore C = \frac{2 \times 865 \times 1.38 \times 0.806 \times 0.96}{17 \times 9.3} = 11.67 \text{ ft.}$$

From a maintenance factor of 0.85 C = 11.67 × 0.85 = 9.9 ft., therefore convenient

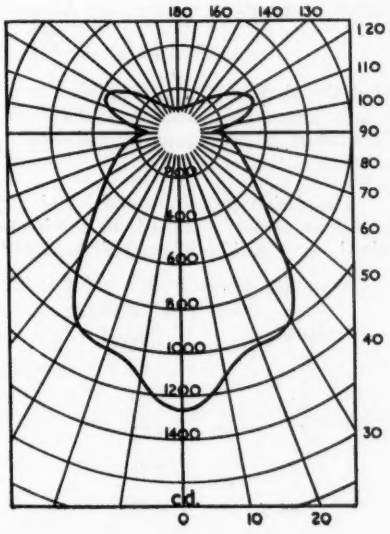


Fig. 10. Intensity distribution curve for lighting fitting used in classroom lighting example.

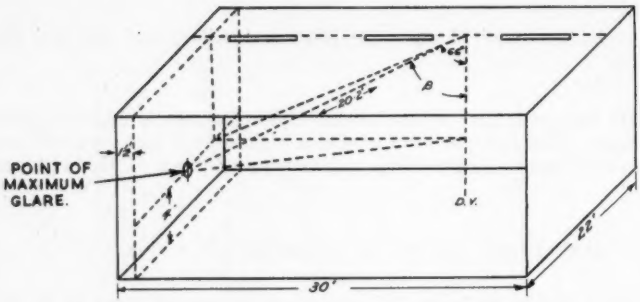


Fig. 11. Diagram showing data used in the calculation of source luminance and area for glare assessment.

spacing between centres along the row is 10 ft., three per row, a total of six fittings for the two rows.

We find therefore by the sector flux method that to obtain the required illumination on the working plane six fittings are sufficient, whereas the environment requires eight. This indicates that the fitting chosen, though not ideal for the purpose, should prove satisfactory. If an ideal fitting had been available these two results would have been identical. The number of fittings required is now known, but economic and architectural aspects have to be considered. A choice of two rows of three general lighting fittings and an additional blackboard fitting would be logical, and this is the layout chosen for the remainder of the example.

Stage (7).

The glare condition can now be assessed.

The worst position in the room will probably be at the back of the class, centrally between rows, at a height of 4 ft. (see Fig. 11). Only those fittings within 45 deg. of the horizontal line of sight have been considered (see Section 5.3). The average luminance of these fittings is 236 ft.-lamberts and the projected area of the four fittings is 0.0179 steradians, see Appendix I. Then

$$K = \frac{236^2 \times 0.0179}{7.5} = 135.$$

Thus the glare will be perceptible but not uncomfortable, and the aim of K = 120 has, in effect, been achieved. This has been confirmed by both the Luckiesh and Guth BCD methods and by Harrison's glare factor tables.

Stage (8).

The design procedure could end there. But to obtain a full knowledge of the brightness pattern achieved the luminance values for a few points have been determined, see Fig. 12. These tally well with the specification.

Example: Considering a point at the middle of the side wall 4 ft. from floor,

	Near row of fittings	Remote row of fittings
Intensity	700 cd.	330 cd. (Fig. 10)
R	8.14 ft.	17.5 ft.
$\frac{X}{R}$	1.54	0.71
$\Delta_a = \Delta_b$	0.02	0.118 (Fig. 2)
$\frac{J}{I_0}$	1.38	1.38 (Fig. 1)
Cos θ	0.676	0.940

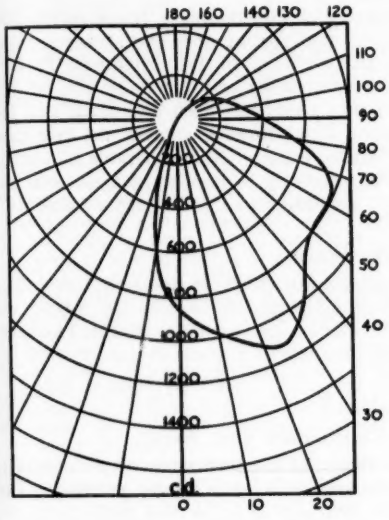
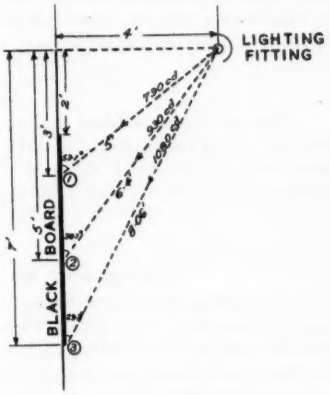


Fig. 12. Intensity distribution curve for lighting fitting used for lighting blackboard in classroom lighting example.

Fig. 13. (below) Diagram showing relative positions of blackboard and its lighting fitting in classroom lighting example.



Then from equation 1.

$$E_d = \frac{700 \times 1.38}{10 \times 8.14}(0.96)\,0.676 + \frac{330 \times 1.38}{10 \times 17.5}(0.764) \times 0.940 = 9.6 \text{ lm./ft.}^2.$$

Since

$$E_t/E_d = 1.60;\ E_t = 9.6 \times 1.60 = 15.4 \text{ lm./ft.}^2.$$

Reflection factor 0.5; luminance 7.7 ft.-lamberts.

Stage (9)

To give comfortable visual conditions and to make the blackboard the focus of visual interest, additional lighting is necessary. This can be provided by an asymmetric 5-ft. 80-watt fitting, see Fig. 12, and the calculation serves as an additional example of the use of the sector flux concept. Referring to Fig. 13, the illumination can be calculated as follows:—

(1) $E_{d1} = \frac{790 \times 1.47}{5 \times 5}(1—0.21—0.21)\,0.800 = 21.6 \text{ lm./ft.}^2.$

(2) $E_{d2} = \frac{930 \times 1.47}{5 \times 6.4}(1—0.26—0.26)\,0.625 = 12.8 \text{ lm./ft.}^2.$

(3) $E_{d3} = \frac{1080 \times 1.47}{5 \times 8.06}(1—0.305—0.305)\,0.495 = 7.6 \text{ lm./ft.}^2.$

Since the total average illumination on this wall from the general lighting is 12.0 lm./ft.^{2}

$E_{t1} = 21.6 + 12.0 = 33.6 \text{ lm./ft.}^2.$
$E_{t2} = 12.8 + 12.0 = 24.8 \text{ lm./ft.}^2.$
$E_{t3} = 7.6 + 12.0 = 19.6 \text{ lm./ft.}^2.$

(9) Conclusion

This investigation has been primarily concerned with finding a reasonably simple method of interior lighting design which enables the type, number and arrangement of lighting fittings to be determined from a consideration of the brightness patterns required in all parts of a room. A method of measuring and expressing the ratio of the direct to total illumination at any point in a room has been described, and this leads to the proposition of a new design method which takes account of the brightness pattern on all surfaces affecting an interior lighting design. A considerable number of measurements with an improved model will be necessary to produce general reference tables which are required to make the method applicable to a wide range of designs.

Acknowledgments

The authors would like to thank their colleagues of the BTH Research Laboratory, and Dr. Hopkinson and his staff at the Building Research Station, for advice and assistance, and to thank Mr. L. J. Davies, Director of Research, the British Thomson-Houston Co., Ltd., for permission to publish this paper.

Appendix I

Calculation of Source Luminance and Area

Use of the glare formula requires a knowledge of the luminance of the source in specific directions. To obtain these values rigorously is not a simple process. One possible method is to obtain luminance distribution curves in the two major axes, but this still necessitates a rather dubious interpolation if the point under consideration does not lie in the plane of either of these axes, and it may be necessary to obtain luminance distribution in additional planes.

The following method is less complex and involves the simplification of considering the source as a plane surface parallel to the floor. It is claimed that for the purposes of glare calculations any error involved will not affect the conclusions reached, as precise values are less important than a knowledge of which criterion of glare will apply to the installation.

To obtain the luminance of a fitting viewed from any point, the intensity per foot in the direction of the point, and in the plane containing the point and the axis of the lamp, is required and in addition the projected area in that direction. The polar distribution in the axis of the source (Ψ function) measured at the downward vertical has been shown to be the same in shape for any other such planes at angles to the downward vertical (see Section 5). So the sector flux at all angles is known and the shape of the Ψ function and consequently the intensity per foot at any point can be obtained.

Assuming a plane source as described above, the projected area falls off as the cosine of the angle of view β. Then since luminance is intensity per unit area

$$B = \frac{I}{A \cos\beta}$$

Furthermore, the solid angle ω required by the glare formula is $\frac{A \cos\beta}{D^2}$. Then using as an example the classroom described earlier and by reference to Fig. 11,

$\beta = 73.5$ deg. $\cos\beta = 0.284$ Area per foot length of fitting $= \frac{6.44}{5}$ sq. ft.

$$I = \frac{136}{5} \text{ cd. per foot.}$$

$$\text{Luminance} = \frac{136 \times \pi \times 5}{5 \times 6.44 \times 0.284} = 236 \text{ ft.-lamberts, and for four fittings in}$$

the 45-deg. field of view $\omega = \frac{4 \times 6.44 \times 0.284}{20.2^2} = 0.0179$ steradians.

Although this calculation is not exact, as mentioned above, when it is noted that the difference between a glare constant of 100 and 200 would be hardly perceptible to a trained observer, the method appears justifiable.

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